PROGRESS REPORT
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Evaluation of Cirrus Cloud Simulations Using ARM Data

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Scientific Goals

Cloud-resolving models (CRMs) provide an effective linkage in terms of parameters and scales between observations and the parametric treatments of clouds used in global climate models (GCMs). They also represent the best understanding of the physical processes acting to determine cloud system lifecycle. ***The goal of this project is to improve state-of-the-art CRMs used for studies of cirrus clouds and to establish a relative calibration with GCMs through comparisons among CRMs, single column model (SCM) versions of the GCMs, and observations.*** This project compares and evaluates a variety of CRMs and SCMs, under the auspices of the GEWEX Cloud Systems Study (GCSS) Working Group on Cirrus Cloud Systems (WG2). The Principal Investigator is chairperson of that working group. ARM data acquired at the Southern Great Plains (SGP) site will be used in planned model comparison case studies. Dr. Mace of the University of Utah, a collaborator under separate funding, leads the preparation of case study data sets using ARM data, including the required definition of environmental and forcing conditions, and data sets suitable for use in evaluating model performance. We lead the model comparison activity and collaborate with Dr. Mace on the analysis of the data. We also conduct our own simulations and analysis for the cases.

Accomplishments

• Completed compilation and analysis of model outputs for the GCSS WG2 Idealized Cirrus Model Comparison Project. Summary of results published in extended abstract attached here. Journal manuscript will be prepared.

• Completed Phase 1 of the GCSS WG2 Cirrus Parcel Model Comparison Project. Summary of results published in extended abstract attached here. Journal manuscript to be submitted shortly.

• Participated in planning for Spring 2000 ARM Cloud IOP via ARM Cloud Working Group. Specifically, sampling strategies were optimized to address key model validation questions identified through the GCSS WG2 Idealized Cirrus Model Comparison Project.

• Facilitated additional flight hours by NASA ER-2 for Spring 2000 ARM Cloud IOP.

• Organized international GCSS Workshop on cloud modeling to be held on July 17-21 at U.K. Meteorological Office College. This is a joint workshop of the GCSS Working Groups on Cirrus Cloud Systems (WG2) and Extratropical Layer Cloud Systems (WG3 under leadership of Brian Ryan, CISRO). Besides furthering their somewhat independent working group goals, objectives and projects, the workshop seeks to foster interaction and coordination between these working groups that have somewhat different perspectives and tools. For example, WG2 is heavily focused on high-resolution cloud models and SCMs while WG3 focuses more on mesoscale to regional models and satellite studies. Agenda attached.

• Completed preliminary analysis of meteorology and cloud conditions for potential cases identified for GCSS WG2 model comparison study. The candidate cases are May 8, 1998, during Spring 1998 Cloud IOP (included SCM IOP), and September 26, 1997, during the Fall 1997 Integrated IOP (included Cloud, Water Vapor and SCM IOPs).

Scientific Highlight

GCSS WG2 Idealized Cirrus Model Comparison Project Results

The 15 models participating in the GCSS WG2 Idealized Cirrus Model Comparison Project represent the state-of-the-art and range in complexity from very high resolution three-dimensional (3-D) large eddy simulation (LES) models, to 3-D and 2-D cloud resolving models (CRMs), to single column model (SCM) versions GCMs. The microphysical (and radiative) components are similarly varied, ranging from simple relative humidity (bulk) schemes to fully size-resolved (bin) treatments of microphysical growth and development. A major finding is that, especially for cold cirrus, the results of the bulk "built-for-cirrus" models diverge systematically and substantially from those of the bin models, even for gross parameters such as horizontally-averaged, vertically-integrated ice water path (IWP) - see figure below. The substantially greater ice water path and internal circulation intensity, and the smaller effective ice water fall speeds (IWC-dependent parameter in some bulk models but requiring bin-by-bin calculation to evaluate in bin models) in the bin model simulations, as well as significant differences in gross cloud geometry (upward growth of cloud top versus relatively static cloud top in bulk model simulations, see Starr et al., 2000, attached here) are all consistent with the occurrence of smaller and more numerous ice crystals in the bin model simulations of cold cirrus. These results serve to strongly focus the science issues needing observational confirmation and provide new insights into how that might be done, even with the present observational limitations and uncertainties.

GCSS Comparison of Cirrus Cloud Models: Ice Water Path

Horizontally-averaged and vertically-integrated ice water path (g m^{-2}) as function of time from cirrus cloud simulations by models participating in the GCSS Idealized Comparison of Cirrus Cloud Models Project. These baseline simulations correspond to nighttime (infrared radiation only) "warm" cirrus (lower panel) and "cold" cirrus (upper panel) cases with cloud top at about –47°C and –66°C, respectively, subject to adiabatic cooling representing a 3-cm s^{-1} uplift over a 4-hour time span followed by a 2-hour dissipation stage. Simulations by cloud resolving models with explicit (bin) microphysics are shown as cyan, by CRMs with bulk microphysics as red, by single column models as green, and by CRMs with heritage in study of deep convection or boundary layer clouds as black (thin). Note the large range of values produced by these state-of-the-art models and also a) the bin and bulk CRM results tend to separately cluster, b) SCMs results span the range of CRM results, and c) heritage models also have very scattered results.

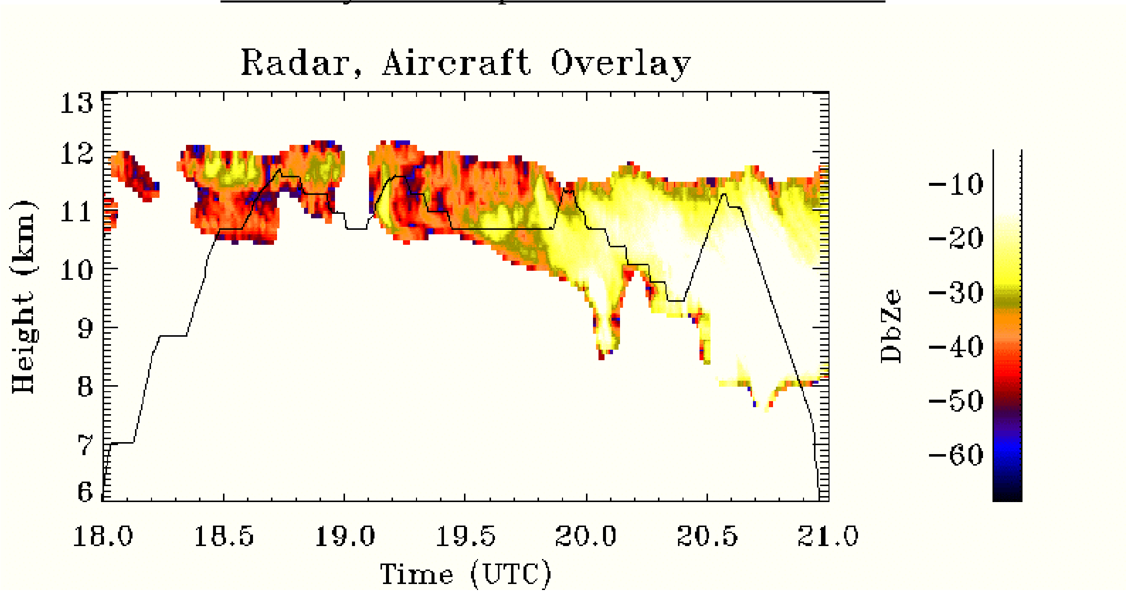
Progress on Evaluation of Cirrus Cloud Simulations Using ARM Data

This project made good progress on the year-1 tasks concerning the GCSS WG2 Idealized Cirrus Model Comparison and Cirrus Parcel Model Comparison Projects (noted in the above list of accomplishments, scientific highlight and also well described in extended abstracts attached to this report). We also made important contributions to planning the Spring 2000 Cloud IOP via the ARM Cloud Working Group. In addition, reasonable progress was made toward initiating a new GCSS cirrus model comparison project focused on one, or more, cirrus cloud cases observed at the ARM SGP site. This latter activity is a main objective of the present project.

Two case were selected for in-depth analysis to determine their suitability for model comparison case studies by GCSS WG2. The candidate cases are May 8, 1998, during Spring 1998 Cloud IOP (included SCM IOP), and September 26, 1997, during the Fall 1997 Integrated IOP (included Cloud, Water Vapor and SCM IOPs). These cases were proposed by Dr. Mace based on inspection of all available cases during IOPs where adequate data were collected. Only cases for which MMCR and airborne *in-situ* observations are available were considered. This limits us to fairly recent IOPs. Criteria for a "good" case are further described below. It is quite clear that a "perfect" case is unlikely, and maybe even undesirable, i.e., the models must begin to face some of the significant challenges such as dealing with significant vertical wind shear.

Our analysis has shown that the May 8 case, while quite interesting, is somewhat problematic. It appears that advection of cloud ice may have been significant in the early period and dominate later on when upper level cloud appeared to be produced by nearby deep convection. The analyzed vertical motion fields at SGP were heavily influenced by the deep convection that was located upwind of the SGP site during this latter time period. Other factors also were not favorable, e.g., strong vertical wind shear in the cloud layer. While the preliminary judgment is that this case is not suitable as a "first" model comparison case study, we may come back to it later due to the strong scientific interest in anvil cirrus.

The September 26 case also has its warts, but is quite interesting nonetheless. The cirrus on this day were associated with a distinct large-scale circulation feature and were associated with the debris field (upper tropospheric moisture) derived from the remnants of Hurricane Nora. This case has been extensively studied and reported by Sassen et al. (http://www.dri.edu/replica/DOE.ARM/doearm97iop/09_26_97case/09_26_97case.html). An MMCR image of the cirrus on this day is shown in the following figure, below which is a tabular summary of the microphysical observations collected by the UND Citation. Of particular note was the observation of triagonal ice crystals in this quite cold cirrus. Analysis of synoptic-scale vertical motion, a necessary parameter to force cloud formation in the models, yielded reasonable and relatively consistent results, as shown in Figure 2. Analysis of the sonde-observed temperature, moisture and wind profiles showed fairly typical features: a relatively neutral layer near cloud top (near vertical section of potential temperature profile) with a relatively stable stratification below (Figure 3). Wind profile data showed fairly strong differences from station to station, Summary of 26 September 1997 observations



Leg #	RH (%)	T (°C)	U (m s^{-1})	Mean Size (μm)	Concen. ($liter^{-1}$)	W_{max} (m s^{-1})
3	80-130	-43	24-20	92-102	0-14	0.7
4	70-100	-50.5	25	86-100	5-50	0.5
5	90-100	-48	25	90-105	5-80	0.8
6	80-90	-45.2	24			0.3
7	90-100	-43	20	96-108	0-100	0.5
8	90-95	-51	25-30	86-92	0-20	0.5
9	90-100	-48.2	15-25	90-110	0-30	0.5
10	90-105	-45.4	22	95-115	0-50	1.0
11						
12						
13	90-105	-42.5-43	20	100-160	0-100	0.9
14	100-115	-40	17.5	153-161	60-105	0.7
15	90-100	-37.5	15	110-165	50-350	0.5
16	95-100	-35	14	130-160	170-280	0.5
17	80-100	-32.5	12.5	110-160	0-200	0.5

Figure 1: MMCR radar reflectivity time-height section for September 26, 1997 case, and tabular summary of microphysical observations along the indicated legs.

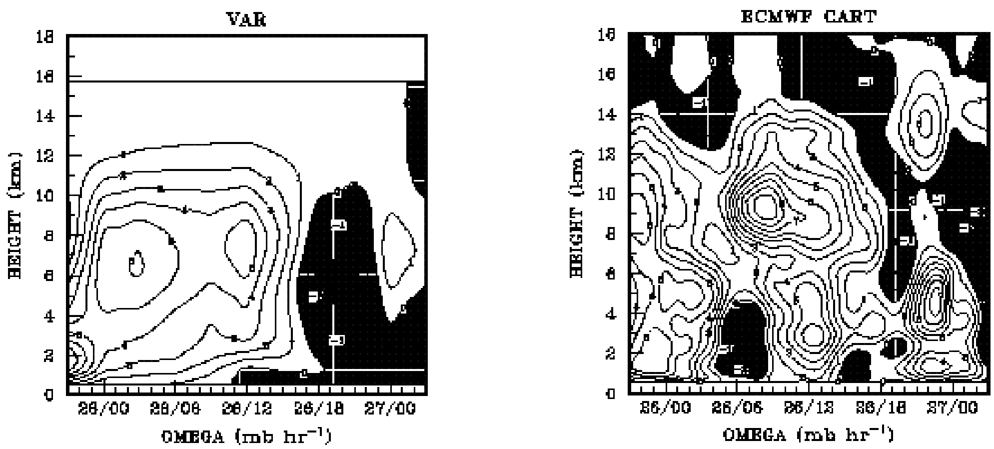


Figure 2: Analysis of vertical motion for September 26, 1997, over ARM SGP site

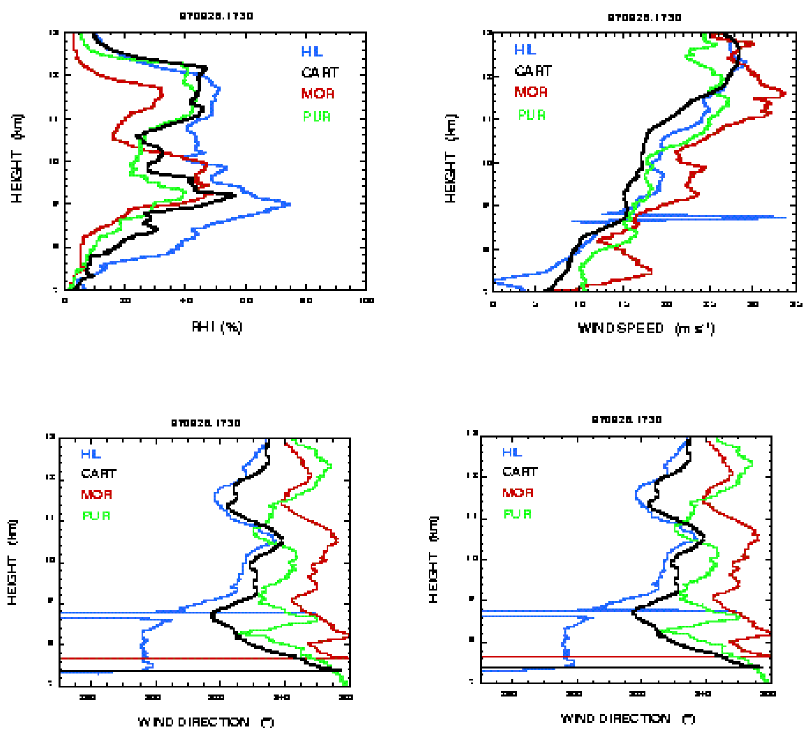


Figure 3: Rawinsonde sounding data for September 26, 1997, case.

but there is an indication of a region of smaller vertical wind shear associated with the cloud formation layer and stronger shear below. It is of note that the relative humidity profiles (shown here with respect to ice) all show values much lower than ice saturation in the cloud forming layer (larger values below). This is an instrumental problem.

In addition, we have analyzed the dynamical data taken during all "level" flight legs for each case using spectral and wavelet transform analysis. The purpose of this analysis is to characterize the intensity and scale of turbulent motions (cloud-scale) versus mesoscale dynamical forcing associated with propagating gravity waves. Shown in Figure 4 is a summary of the vertical motion data for the September 26 case where the data has been de-trended and then bandpass filtered as shown in Figure 5. It is seen that the vertical motion field is dominated by larger scales, the signal at about 5-7 km is quite strong. Further information about this case, and the May 8 case may be found at: http://www.met.utah.edu/mace/homepages/research/archive/sgp.html.

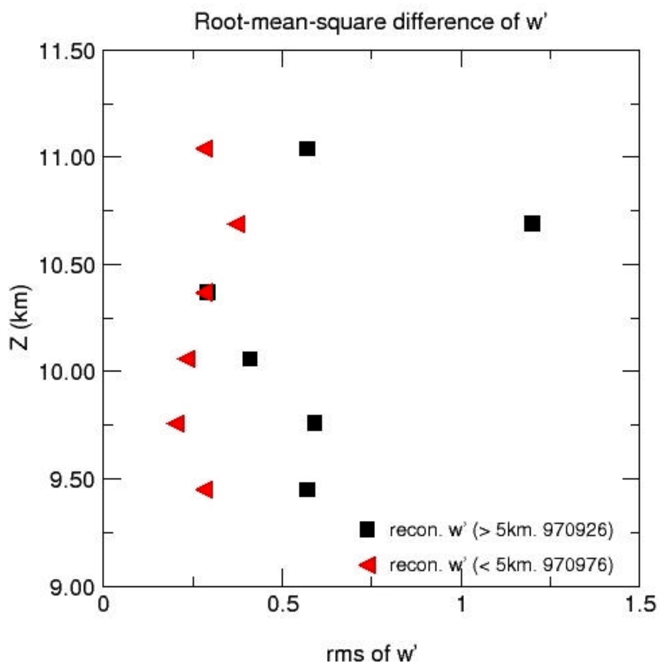


Figure 4: Analyzed vertical motions observed by UND Citation on September 26, 1997.

At the upcoming GCSS WG2 workshop, both these cases, as well as additional possible cases from the Spring 2000 Cloud IOP will be considered as we press toward a decision on a first case. Our expectation is that a case will be selected, September 26 is likely, and that we will develop the necessary data sets and protocols for the model comparison in the next few months such that preliminary simulation results are available before the end of 2000. A report on the workshop will be produced and appended to this report. Additional information about GCSS WG2 and this project may be found at URL: http://eos913c.gsfc.nasa.gov/gcss_wg2/.

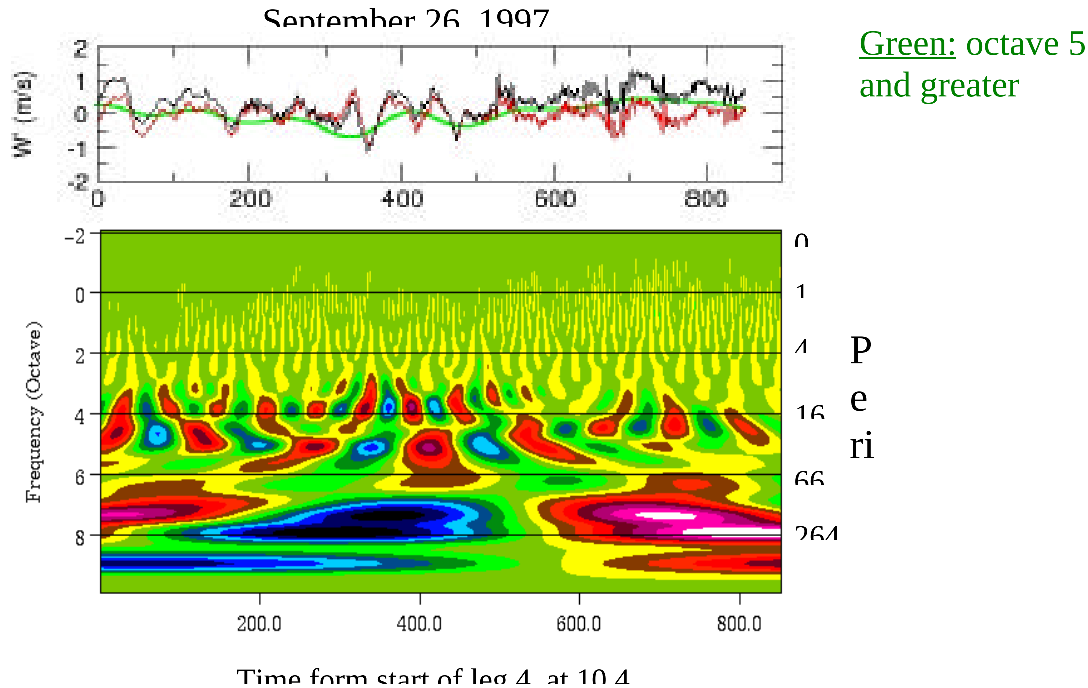


Figure 5: Wavelet transform analysis of vertical motion data from UND Citation during September 16, 1997 cirrus case. True airspeed was about 100 m s-1 so that the 212 s (800 * 0.25) section shown here corresponds to a length of about 21 km. Note that octave 4 corresponds to a period of about 16 s (1.6 km wavelength).

Background: Practical Considerations

An initial observational case study model comparison project is greatly facilitated by:

- relatively simple and homogeneous cirrus cloud system,

- single-layer cirrus-alone cloud system.

Complex multilayered cases or dynamically complex cases are not so amenable to simulation for evaluation of the models. For example, the presence of boundary layer clouds obscures the important surface-based remote sensing observations and degrades the data quality. Highly inhomogeneous cloud systems present difficulties in establishing the statistical validity or representativeness of the correlative validating observations.

Another factor is the poor knowledge of upper tropospheric humidity. While ARM and its Water Vapor IOPs continue to push capabilities in this area, the data are still deficient. However, the data can be subjectively "corrected" with reasonable results. This is especially true of sonde data if

- adequate high-quality airborne *in-situ* humidity data are available.

Of more concern is poor knowledge of vertical motion forcing to cirrus cloud formation or maintenance. Cirrus clouds often form in response to relatively weak forcing of a few cm s^{-1} that is comparable to the uncertainty in analyses of such forcing. This is particularly problematic as differences in IWP between simulations over a range of a few cm s^{-1} are comparable to "physics" uncertainties. Thus, cases are sought where there is

- good agreement between vertical motions analyzed by various centers, such as ECMWF, NCEP and ARM VAR (variational analysis), indicative of a dynamical situation that is not complex and reasonably well characterized.

Even if cases satisfying such conditions are found, it is still likely that simulations will be performed for a range of specified vertical motions spanning the estimated uncertainty.

Strong vertical shear of the horizontal winds presents real difficulties for CRM simulations. many of the models have not be previously applied to such conditions. In a strongly sheared case, strong inflow/outflow across the model domain boundaries is unavoidable. There are two approaches (2-Dimensional and 3-Dimensional Models) to dealing with such an environment. The first approach is to employ cyclic (periodic) lateral boundary conditions. However, the mean flow state becomes altered via vertical mixing which usually leads to numerical difficulties (inconsistencies). Also, internal cloud dynamics dissipate (run down) via mixing processes unless reinforced somewhat artificially. Capturing a realistic cloud lifecycle is major challenge using cyclic boundary conditions. The second alternative is to use open boundary conditions where the inflow is directly specified from data or from a larger scale model (nested-grid approach). However, internal heating and mixing process within the model domain, but not in the external environment, can cause significant imbalance across the boundaries. Also, imperfect boundary conditions at the grid interface between the LES-domain and the external domain tend to generate "noise" via refection of disturbances at the downwind boundary which rapidly propagate back into the domain. While such difficulties can be avoided or minimized in low shear cases by letting the model domain float with the mean wind, they are unavoidable when strong shear is present. Though strong wind shear is common in cirrus cloud systems, it is likely that shallow layers of low shear are associated with the cloud generating layer in many cases. This is somewhat supported by observational evidence (Quante and Starr, 2000). In any event, the model comparison project will be facilitated by:

- relatively small vertical wind shear.

Alternatively, cases with low shear at least in the cloud generating layer may be suffice as an initial case. The latter may not be adequately determinable from sonde data alone, or from 50-MHz wind profiler observations, but may require airborne in-situ observations.

Finally, given the inherent high spatial/temporal variability of most cirrus cloud systems, the statistical robustness of correlative data on cloud layer properties, especially cloud ice water content is required. It is only through the combination of airborne in-situ data and surface-based remote sensing data, especially mm-radar, that anything approaching an adequate data sample can be obtained. Thus, further requirements are:

- good coverage by MMCR
- high quality airborne microphysical data.

Refereed Publications this year from this Project - none

Recent Project-Related Publications

Randall, D., J. Curry, P. Duynkerke, S. Krueger, M. Miller, M. Moncrieff, B. Ryan, D. Starr, W. Rossow, 2000: The Second GEWEX Cloud System Study Science Plan. 104 pp. (soon to be released)

Starr, D.O'C., 2000: GEWEX Cloud System Study Working Group II - Cirrus Cloud Systems, 1999 Report. 18 pp.
available from: http://eos913c.gsfc.nasa.gov/gcss_wg2/Documentation.html

Starr, D.O'C., 2000: GEWEX, ARM and EOS Terra Plan a Coordinated Observing Period. *GEWEX News*, 10(2), 12.

Extended Abstracts Published

Starr, D.O'C., A. Benedetti, Matt Boehm, P.R.A. Brown, K.M. Gierens, E. Girard, V. Giraud, C. Jakob, E. Jensen, V. Khvorostyanov, M. Koehler, A. Lare, R.-F. Lin, K.-I. Maruyama, M. Montero, W.-K. Tao, Y. Wang, and D. Wilson, 2000: Comparison of Cirrus Cloud Models: A Project of the GEWEX Cloud System Study (GCSS) Working Group on Cirrus Cloud Systems. *Proceedings*, 13th International Conference on Clouds and Precipitation, 14-18 August 2000, Reno, Nevada.

Lin, R.-F., D.O'C.Starr, P.J. DeMott, R. Cotton, E. Jensen, K. Sassen, 2000: Cirrus Parcel Model Comparison Project Phase 1. *Proceedings*, 13th International Conference on Clouds and Precipitation, 14-18 August 2000, Reno, Nevada.

Other ARM-Related Refereed Publications this year by these Investigators

Demoz, B., D. Starr, D. Whiteman, K. Evans and D. Hlavka, 2000: Raman LIDAR detection of cloud base. *Geophys. Res. Lett.*, in press.

Whiteman, D.N., K.D. Evans, B. Demoz, D.O'C. Starr, D. Tobin, W. Feltz, G.J. Jedlovec, S.I. Gutman, G.K. Schwemmer, M. Cadirola, S.H.Melfi, F.Schmidlin, 2000: Raman lidar measurements of water vapor and cirrus clouds during the passage of Hurricane Bonnie. *J. Geophys. Res.*, accepted.

Appendices

A. Agenda of Joint GCSS WG2-WG3 Cloud Modeling Workshop in July 2000

B. Starr et al., 2000 - extended abstract for ICCP in August 2000

C. Lin et al., 2000 - extended abstract for ICCP in August 2000

Joint WG2-WG3 GCSS Workshop
U.K. Meteorological Office College
17-21 July, 2000

Preliminary Program

Monday

9:00 - 9:15		Welcome (B. Ryan, D. Starr, UKMO)
9:15 - 9:45		The New GCSS Science Plan (D. Randall)
9:45 - 10:30		Cloud Parameterization in the UKMO Unified Model (D. Gregory, D. Wilson, A. Bushel)
10:30 - 11:00	*Break*	
11:00 - 12:00		Cloud Parameterization in the UKMO Unified Model (continued)
12:00 - 13:15	*Lunch*	
13:15 - 15:00		FASTEX Intercomparison (P. Clark, H. Lean)
15:00 - 15:30	*Break*	
15:30 - 17:00		Fastex Intercomparison Discussion (Chair: P. Clark)

Tuesday

8:30 - 10:00		WG2 Idealized Cloud Model Comparison Project (D. Starr)
10:00 - 10:30	*Break*	poster: 3D Numerical Simulations of Cirrus Clouds by GESIMA (K.-I. Maruyama)
10:30 - 10:50		Comparison of Cloud-resolving Simulations of Cirrus Cloud with Observations (P. Brown)
10:50 - 11:10		Simulations of Cirrus Clouds by GCEM (Y. Wang, D. Starr)
11:10 - 12:00		Idealized Comparison Discussion (Chair: P. Brown)
12:00 - 13:15	*Lunch*	
13:15 - 15:00		WG3 Sensitivity Experiment Results: Fall Speed, Sublimation, and RH Sensitivity (presentations by WG3 members)
15:00 - 15:30	*Break*	
15:30 - 17:00		Discussion of Results and Implications for GCMS (Chair: B.Ryan)

Wednesday

8:30 - 9:30		Aersols and Their Effects in GCMs (U. Lohmann)
9:30 - 10:30		WG2 Cirrus Parcel Model Comparison Project (R.-F. Lin)
10:30 - 11:00	*Break*	

Joint WG2-WG3 GCSS Workshop
U.K. Meteorological Office College
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Wednesday (continued)

11:00 - 11:30	Ice Nucleation in Lee-wave Clouds (R. Cotton)
11:30 - 12:15	Discussion of Aerosol Issues (Chair: P. Brown)
12:15 - 13:30 *Lunch*	
13:30 - 15:00	Large-scale Cloud Survey Techniques (Chair: G. Tselioudis)
15:00 - 15:30 *Break*	
15:30 - 17:30	Large-scale Cloud Survey Techniques (continued)
Evening	*Skittles at local pub*

Thursday

8:30 - 9:30	Tropical Cirrus Clouds (M. Boehm)
9:30 - 10:00	Ice Crystal Concentration at Cold Cloud Tops (A. Heymsfield)
10:00 - 10:30 *Break*	
10:30 - 12:00	Subgrid Cloud Variability in GCMs (C. Jakob)
12:00 - 13:15 *Lunch*	
13:15 - 13:45	ARM Spring 2000 Cloud IOP (J. Mace)
13:45 - 14:15	New MODIS Cirrus Cloud Models (B. Baum)
14:15 - 14:45	Short-wavelength Radar for Cloud Studies (A. Illingworth)
14:45 - 15:15 *Break*	
15:15 - 17:30	WG2 and WG3 Working Sessions (separate)
	- New and Future Projects
	- Observational Requirements and Field Experiments

Friday

8:30 - 9:30	WG2 and WG3 Working Sessions (continued)
9:30 - 10:00	Meeting Summary - WG3
10:00 - 10:30 *Break*	
10:30 - 11:00	Meeting Summary - WG2
11:00 - 12:00	Discussion of Possible Joint WG2-WG3 Activities
12:00	Close of Workshop

13th International Conf. on Clouds and Precipitation
August 14-18, 2000, Reno, Nevada

COMPARISON OF CIRRUS CLOUD MODELS: A PROJECT OF THE GEWEX CLOUD SYSTEM STUDY (GCSS) WORKING GROUP ON CIRRUS CLOUD SYSTEMS

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1. INTRODUCTION

The GEWEX Cloud System Study (GCSS, GEWEX is the Global Energy and Water Cycle Experiment) is a community activity aiming to promote development of improved cloud parameterizations for application in the large-scale general circulation models (GCMs) used for climate research and for numerical weather prediction (Browning et al., 1994). The GCSS strategy is founded upon the use of cloud-system models (CSMs). These are "process" models with sufficient spatial and temporal resolution to represent individual cloud elements, but spanning a wide range of space and time scales to enable statistical analysis of simulated cloud systems. GCSS also employs single-column versions of the parametric cloud models (SCMs) used in GCMs. GCSS has working groups on boundary-layer clouds, cirrus clouds, extratropical layer cloud systems, precipitating deep convective cloud systems, and polar clouds.

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Central to the GCSS strategy is the conduct of model comparison projects. These systematic comparisons document the performance of state-of-the-art models, detect problems with specific models, and identify fundamental issues resulting in significant inter-model differences, such as the approach to representing a specific process. Comparison to field observations, especially in a case study mode, is another cornerstone of the GCSS approach. The concept is that these activities will serve to markedly accelerate community-wide improvements in CSMs, as well as to provide better focus for planned field experiments in terms of key science issues related to the modeling of cloud systems. CSMs are quite well matched, in terms of scales and resolved physical processes, for such comparisons with observations. Moreover, when sufficient confidence is established in the models via validation versus field measurements, CSMs can serve as highly useful research platforms for the development of concepts and approaches to cloud parameterization because they do resolve the physical processes operating in cloud systems to a much greater extent than SCMs. While some processes must still be parameterized in CSMs, such parameterizations are more focused, in terms of the represented physical process, and better correspond to the scales at which such processes actually operate.

2. IDEALIZED CIRRUS MODEL COMPARISON

The GCSS Working Group on Cirrus Cloud Systems (WG2) is conducting an Idealized Cirrus Model Comparison Project where cirrus cloud simulations by a variety of cloud models are compared for a series of idealized situations with relatively simple initial conditions and forcing. *Preliminary* results of this activity are reported herein. A second WG2 project, Cirrus Parcel Model Comparison, is reported in a companion paper in this volume (Lin et al., 2000). In the present project, results were submitted from 16 distinct models, including 3-dimensional large eddy simulation (LES) models, 2-dimensional cloud-resolving models (CRMs), and SCMs. The microphysical components of the models range from single-moment bulk (relative humidity) schemes to sophisticated size-resolved (bin) treatments where ice crystal growth is explicitly calculated. Radiative processes are also included in the physics package of each model and are similarly varied.

The baseline simulations include nighttime "warm" cirrus and "cold" cirrus cases where cloud top initially occurs at about –47°C and –66°C, respectively. The cloud is generated in an ice supersaturated layer about 1 km in depth (120% in 0.5 km layer) with a neutral ice pseudoadiabatic thermal stratification (Fig. 1).

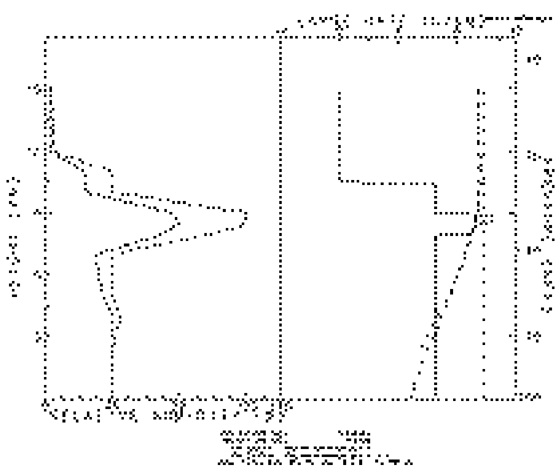

Figure 1: Relative humidity, relative humidity with respect to pure ice, and temperature lapse rate profiles for the "warm" cirrus case. Reference lapse rates corresponding to neutral stratification for ice pseudoadiabatic and dry adiabatic processes are also shown. Profile shape is similar for the "cold" cirrus case.

Away from cloud forming region, ambient conditions correspond to the Spring/Fall 45°N and Summer 30°N standards, where the tropopause occurs more than 1 km above the nominal cirrus layer in the "warm" and "cold" cirrus cases, i.e., at -56°C at 10.5 km and -75.5°C at 15.5 km, respectively.

Continuing cloud formation is forced via an imposed diabatic cooling representing a 3 cm s^{-1} uplift over a 4-hour time span followed by a 2-hour dissipation stage with no imposed "ascent" cooling. Variations of the baseline cases include no-radiation and stable-thermal-stratification cases.

The time-dependent behavior of the vertically-integrated and horizontally-averaged ice water path (IWP) are shown in Fig. 2 for the "warm" (lower panel) and "cold" (upper panel) cirrus comparisons (neutral stratification, infrared only). This is the grossest measure of model response to the prescribed conditions.

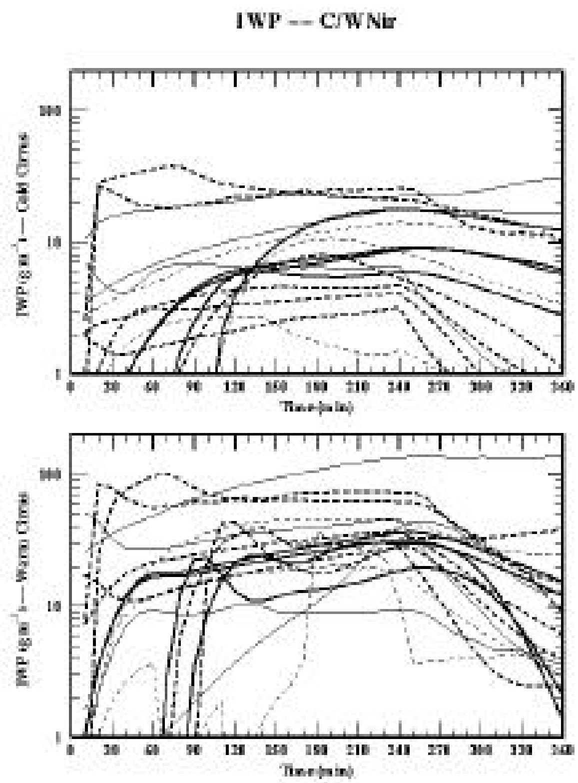

Figure 2: Time-dependent behavior of IWP (g m^{-2}) in simulations of "cold" (upper panel) and "warm" (lower panel) cirrus clouds with 16 cloud models -- see text for detailed description and explanation.

Results are shown for 16 models including 3 SCMs. Specific models are not identified here. Though somewhat arbitrary, the results are distinguished in terms of model heritage and design. Results from models built primarily to be cirrus models or with a strong cirrus heritage are shown by the heavy dashed or heavy solid lines. The heavy dashed lines denoted results from models with a bulk treatment of cloud microphysics while the heavy solid lines indicate results from models with highly detailed bin treatments of cirrus cloud microphysical development. Thin dashed lines correspond to results from SCMs and the thin solid lines indicate models originally developed to treat deep convective cloud systems.

It is immediately obvious that a wide range of model response is found even in IWP (factor of 10). Focusing on the "cold" cirrus comparison, two significant groupings are evident. The bulk microphysics "cirrus heritage" models tend to behave in a similar manner. The "bin" models also group. The results from SCMs and models with a deep convection heritage yield results roughly spanning the range of the others. We will focus here on the cirrus heritage models.

Cloud formation is delayed in the bin models relative to the bulk models. All models employed an initial random field of weak thermal perturbations (0.02°C maximum). Thus, while the bulk models immediately respond to supersaturated conditions, the bin models wait until local conditions achieve sufficient relative humidity (up to 140% or more), via circulation, to trigger nucleation (Lin et al., 2000).

However, larger IWP is achieved in the bin models and is better maintained after the "ascent" forcing is turned off at 240 minutes. IWP is dissipated much more rapidly in the bulk models after this time. Even within these groups, differences amount to better than a factor of 2 at 240 minutes and are significantly greater at later times in the cold cirrus comparison. Results are more confused in the warm cirrus case where the overall spread is less (120-240 min.) and IWP declines precipitously after 240 minutes in most models. It should be noted that observations of "warm" cirrus have been much more plentiful than for cirrus at very cold temperatures and may be partly responsible for the greater convergence of results in the warm case.

Shown in Fig. 3 is a measure of circulation intensity within the cloud layers for the bulk and bin cirrus heritage models. Note that the simulations begin from a resting state. Focusing again on the cold cirrus case (top panel), two groups are again apparent. The models yielding the most dynamically energetic simulations of the cirrus heritage modles are the bin models. The bulk models produce significantly less intense circulation. Clearly, the two classes of models exhibit fundamentally different behavior for the cold cirrus case. As with IWP, the distinction is less clear for the warm cirrus case.

Another gross measure of model response is the location of cloud top and base. Shown in Fig. 4 are the locations of cloud top and cloud base, and the cloud thickness at 240 minutes in the cold cirrus simulations. These altitudes are determined by applying a suitable threshold to the horizontally-averaged ice water content profile where the same threshold is used for all the models. A range of more than 1 km is found in the

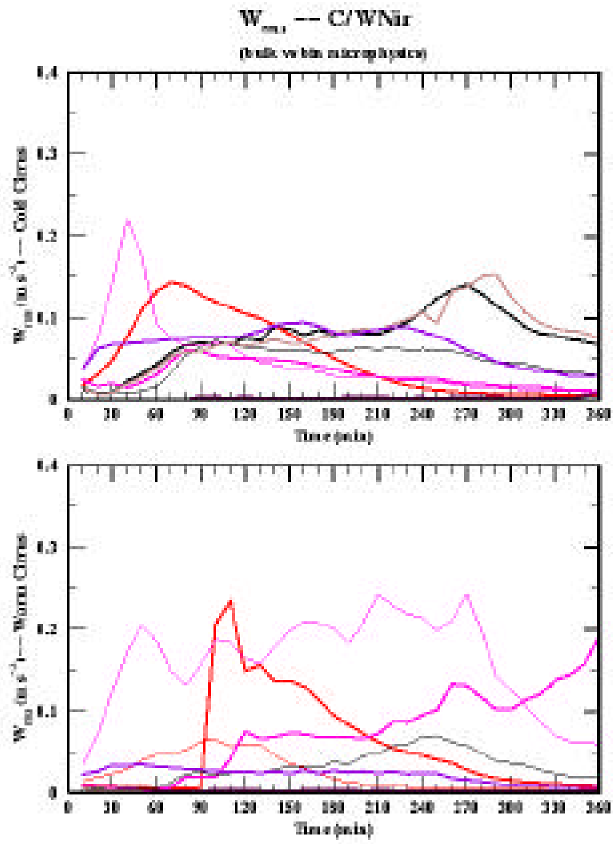

Figure 3: Time-dependent behavior of root mean square vertical velocity in the cloud forming region during simulations of cold (upper panel) and "warm" (lower panel) cirrus clouds by "cirrus heritage" models. See text for further explanation.

location of cloud top. Cloud base varies by more than 2 km among the models while cloud thickness ranges from 1.5 km to more than 4 km. This is a remarkable degree of inter-model difference.

To first order, these fundamental differences can be traced to differences in the size distribution of the ice crystal population represented in the two different classes of models. The bin models tend to have smaller, and consequently much more numerous, ice crystals while the bulk model are dominated by larger crystals, whether explicit or assumed. The primary effect of the differences in ice crystal size distribution is on the diagnosis of ice water fall speed. This was explicitly confirmed via calculations of an effective ice water fall speed integrated across the particle spectrum done within the bin models as part of this comparison project (not so easy a task). As noted by Starr and Cox (1985b), the ice water fallout process has a dominant effect on the vertical distribution of ice water and on the intensity of circulation within cirrus clouds. In the bin models, cloud top tends to grow upward while it is relatively static in the bulk models. Correspondingly, the ice water content profiles are peaked more toward cloud top in the bin model simulations while the bulk models exhibit peak ice water content at a level below the middle of the cloud, much as seen in Starr and Cox (1985a). The downward extension of cloud base is enhanced in models with larger ice crystals.

As stated above, the relative agreement found in the warm cirrus case may be partly attributed to the availability of observations of "warm" cirrus clouds. Moreover, it should be noted that for homogeneous nucleation processes, disagreements among parcel models, from which the microphysical treatments in multi-dimensional bin models are derived, are significantly enhanced in the cold regime (Lin et al., 2000). The same ambient aerosol populations used in the WG2 Cirrus Parcel Model Comparison Project was also used here by the models requiring this information.

An additional set of experiments was performed in which the ice water fall speed was set to fixed values for all crystals, irregardless or size or habit. Values of 20 cm s^{-1} and 60 cm s^{-1} were used. The intent was to trick the bin models into behaving like the bulk models and vice versa, i.e., these values are roughly representative of the effective ice water fall speeds found in these model classes, respectively. The results largely confirmed the present interpretation. Tests of radiative impact (present versus no radiation simulations) revealed a consistent effect but not one that alters the present conclusion, i.e., relative to present simulation by each model, the no-radiation simulation produced similar relative changes.

3. CONCLUSIONS

While the present results may at first appear discouraging, they can also be seen to indicate that significant progress can be made in the very near future. The disagreements are substantial. Present observational capabilities, including recent advances in measurement of small ice crystal populations, should be able to adequately resolve the shape of the ice water content profile and the overall ice water path. The result that internal cloud dynamical intensity is highly correlated with ice crystal size distribution allows an additional confirming test that is within present measurement capability. Observations of bulk ice water fall speed are also now being derived from mm-wavelength Doppler radar. Further information about GCSS WG2 and its projects may be found at the GCSS WG2 webpage: http://eos913c.gsfc.nasa.gov/gcss_wg2/

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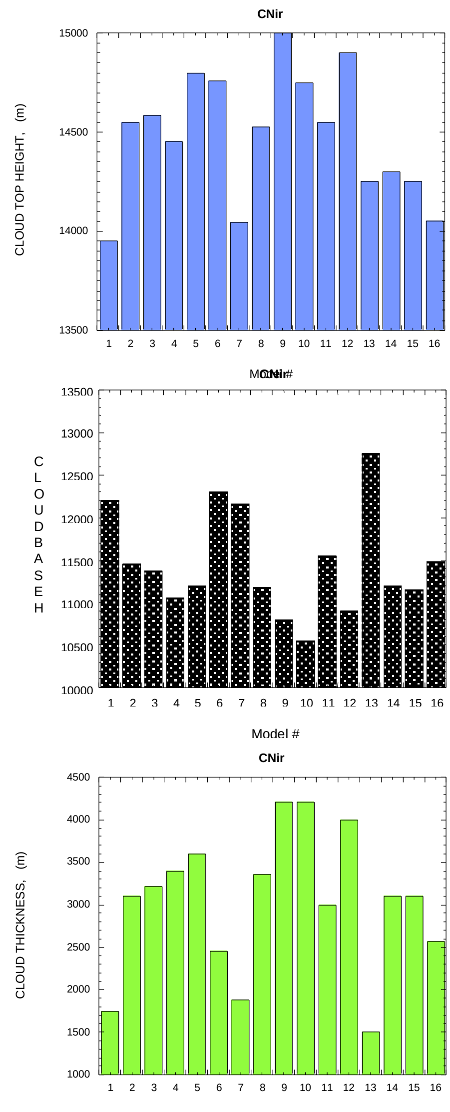

Figure 4: Distribution of cloud top (upper), cloud base (lower) locations, and corresponding cloud thickness for simulations of cold cirrus case. See text for discussion.

CIRRUS PARCEL MODEL COMPARISON PROJECT PHASE 1

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1 INTRODUCTION

The Cirrus Parcel Model Comparison (CPMC) is a project of the GEWEX Cloud System Study Working Group on Cirrus Cloud Systems (GCSS WG2). The primary goal of this project is to identify cirrus model sensitivities to the state of our knowledge of nucleation and microphysics. Furthermore, the common ground of the findings may provide guidelines for models with simpler cirrus microphysics modules.

Table 1: Simulation identifiers.

W [m/s]	*0.04*	*0.2*	*1*
HN-ONLY	Ch004	Ch020	Ch100
	Wh004	Wh020	Wh100
ALL-MODE	Ca004	Ca020	Ca100
	Wa004	Wa020	Wa100
HN-λ-fixed		Ch020L	
		Wh020L	

We focus on the nucleation regimes of the warm (parcel starting at $-40°$C and 340 hPa) and cold ($-60°$C and 170 hPa) cases studied in the GCSS WG2 Idealized Cirrus Model Comparison Project [*Starr et al.,* 2000]. Nucleation and ice crystal growth were forced through an externally imposed rate of lift and consequent adiabatic cooling (Table 1). The background haze particles are assumed to be lognormally-distributed H_2SO_4 particles. Only the homogeneous nucleation mode is allowed to form ice crystals in the HN-ONLY runs; all nucleation modes are switched on in the ALL-MODE runs. Participants were asked to run the HN-λ-fixed runs by setting $\lambda = 2$ (λ is further discussed in section 2) or tailoring the nucleation rate calculation in agreement with $\lambda = 2$[1]. The depth of parcel lift (800 m) was set to assure that parcels underwent complete transition through the nucleation regime to a stage of approximate equilibrium between ice mass growth and vapor supplied by the specified updrafts.

2 MODEL DESCRIPTIONS

Five parcel modeling groups participated in the CPMC (Table 2). Hereafter, we will refer to these models as the C, D, J, L, and S models, respectively, as denoted in the table.

The estimate of the nucleation rate of ice in solution droplets, J_{haze}, remains an active research area. J_{haze} was computed using either (1) the modified classical theory approach (model J) or (2) the effective freezing temperature approach (hereafter, T_{eff} models, models C, D, L, S).

The T_{eff} models attempt to directly link measured J_{haze} to nucleation rates of equivalent-sized pure water droplets J_w via the effective freezing temperature, which is defined as

$$T_{eff} = T + \lambda \Delta T_m, \tag{1}$$

such that $J_{haze} = J_w(T_{eff})$ as introduced by *Sassen and Dodd* [1988]. In (1), ΔT_m is the equilibrium melting point depression (positive valued), which depends on solute wt%, and λ is an empirical coefficient to account for additional suppression/enhancement of nucleation temperature due to

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[1]Note that $\lambda = 2$ agrees approximately with data presented by *Koop et al.* [1998].

Table 2: Participant cirrus parcel models.

Organization *Investigator*	*UKMO* *Cotton (C)*	*CSU* *DeMott (D)*	*ARC* *Jensen (J)*	*GSFC* *Lin (L)*	*U. Utah* *Sassen (S)*
Bin characteristic[a]	discrete	continuous	continuous	continuous	particle tracing
Haze size[b]	r_{eq} or $\frac{dr}{dt}$	r_{eq}	r_{eq}	r_{eq}	r_{eq} or $\frac{dr}{dt}$
λ	1.5	1.5	varying[c]	1.0	1.7
deposition coef. β_i	0.24	0.04	1	0.1	0.36
References	*Spice et al.* [1999]	*DeMott et al.* [1994] *DeMott et al.* [1998]	*Jensen et al.* [1994] *Tabazadeh et al.* [1998]	*Lin* [1997]	*Sassen and Dodd* [1988] *Sassen and Benson* [2000]

[a] Discrete vs continuous binning indicates if assuming that all particles have exactly the same size in a given size bin or a certain distribution of particle sizes is allowed in a bin.
[b] r_{eq} vs. $\frac{dr}{dt}$ denotes either using the equlibrium-sized haze approximation or computing the diffusional growth of haze particles explicitly.
[c] See section 2 for detailed discussion.

non-ideal interaction between ions and condensed water. Although *Sassen and Dodd* [1988] noted that an average λ for different solutions was around 1.7, values for specific solutions may range from 1 to 2.5.

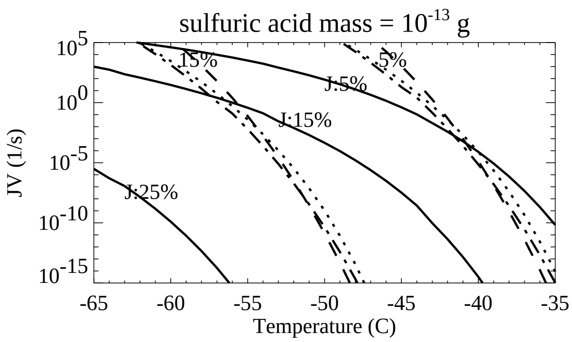

Figure 1: $J_{haze}V$ vs. temperature for solute wt% 5, 15 and 25%. Solid, dashed, dash-dotted, dotted curves denote models J, C, S, models D and L (same curves), respectively, for $\lambda = 2$.

In model J, recent direct data on ice/solution surface tension was incorporated and activation energy was inferred from recent laboratory measurements of J_{haze} for H_2SO_4 particles following *Tabazadeh et al.* [1997] and *Koop et al.* [1998]. This approach to determine J_{haze} can be interpreted as a T_{eff} scheme with varying λ (Figure 1). The intrinsic λ varies inversely with solute wt% and temperature. Also, the differences in the sensitivity of $J_{haze}V$ (V is the volume of the particle) to solute wt% between these two approaches may lead to systematic differences in the freezing haze size distributions. Nucleation rate data over a wide range of values, e.g., data points beyond critical freezing conditions, are needed to diminish the inconsistency between the two approaches.

Little constraint was imposed on formulating heterogeneous nucleation because theoretical and experimental understanding are still quite poor. Models C and L employ ice saturation ratio dependent parameterizations of activated IN following *Spice et al.* [1999] and *Meyers et al.* [1992], respectively. These parameterizations are expected to represent a maximum heterogeneous nucleation impact.

Haze particles of the given H_2SO_4 aerosol distribution are subject simultaneously to heterogeneous and homogeneous nucleation in models D and S. The number concentration of the activated IN in model D is computed following *DeMott et al.* [1998] based on field experiment data. This treatment was expected to yield the most conservative estimate of IN in cirrus. Model S computes the activated freezing nuclei using T_{eff} dependent Fletcher equation [*Sassen and Benson,* 2000], where parameters were set to yield the most favorable conditions for heterogeneous nucleation.

Participants either assumed that haze particles are in equilibrium with the environment or computed the diffusional growth of haze particles directly (Table 2). The diffusional growth rate of haze particles more or less exponentially decreases with temperature as caused by water vapor saturation pressure. The response time scale to the deviation from equilibrium can be considerably greater than one model time step in a swift updraft in a cold environment. Therefore, large haze particles may become more concentrated than the corresponding equilibrium-size particles in such conditions. This may result in considerable delaying of haze growth in models C and S (Table 2) and affect ice particle formation rate.

3 RESULTS AND DISCUSSIONS

As we proceed to describe the results and differences between models, it must be noted that the benchmark is not necessarily the median or the average of model results. The predicted N_i (ice number concentration) at 800 m above the starting point is compared (Fig. 2). In the HN-ONLY cases, to a first order approximation, the logarithm of N_i increases quasi-linearly with the logarithm of updraft speed. The predicted N_i by models D, S and L are close; N_i by models J and C form the lowest and highest bounds in the six cases, respectively.

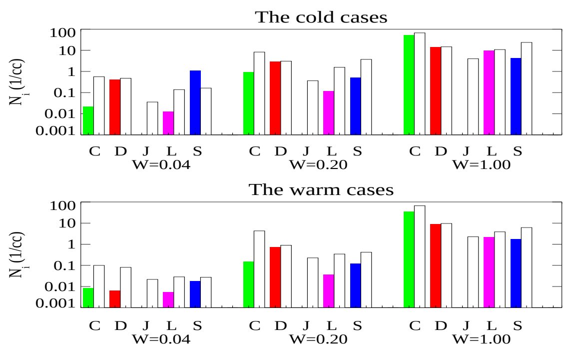

Figure 2: N_i predicted vs imposed updraft speed. The unfilled and filled bars denote HN-ONLY and ALL-MODE, respectively.

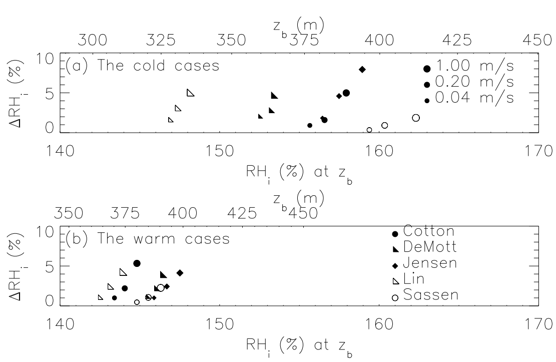

Figure 3: The RH_i at cloud base z_b ($N_i = 1$ liter^{-1}) and the corresponding ΔRH_i, defined as the difference between peak RH_i and RH_i at z_b (the HN-ONLY cases).

Cirrus initiation occurred over a narrower range of altitude and RH_i (relative humidity over ice) in the warm HN-ONLY cases than in the cold cases (Fig. 3). The increasing sensitivity of the cloud base RH_i as temperature decreases in the four T_{eff} models is primarily caused by λ.

Heterogeneous nucleation is a possible explanation of the discrepancy between the observed threshold RH_w for cirrus formation and the theoretically derived threshold RH_w (relative humidity over water) for homogeneous nucleation of H_2SO_4 or $(NH_4)_2SO_4$ solution particles; e.g., [*Heymsfield and Miloshevich,* 1995]. Cirrus properties are affected by the dominant nucleation mode in cloud initiation because of the distinct characteristics of the two modes.

The cloud base height, RH_i and peak RH_i in the ALL-MODE cases (not shown) vary even more because of our respective unbounded choices of heterogeneous nucleation. The impact of heterogeneous nucleation on lowering N_i, peak RH_i, and cloud formation altitude is extremely sensitive to the onset conditions for nucleation and the subsequent ice particle formation rate. With heterogeneous nucleation, the peak RH_i is lower in all but the case Wa100 by model S. The predicted N_i is reduced in all but the case Ca004 by model S.

We now discuss the results of the HN-λ-fixed simulations. The nucleation regimes of Wh020L and Ch020L take place within the temperature range of -43.2 to -44.2°C and -63.2 to -64.2°C, respectively. The effect of temperature variation on nucleation rates within this 1°C range is secondary, compared to the evolution of haze solute wt%. Thus, it is justified to analyze and visualize results according to the $z - z_b$ coordinate (Fig. 4).

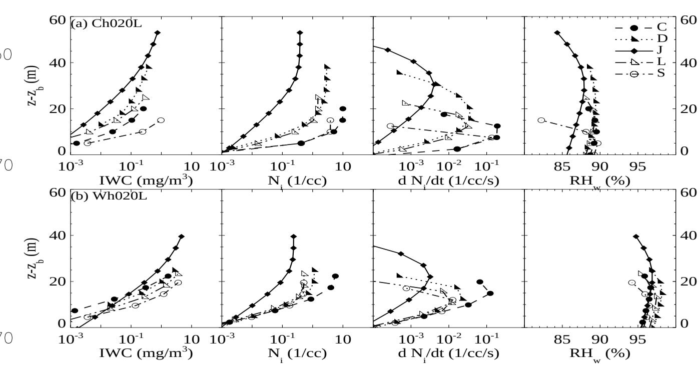

Figure 4: Ice water content (IWC), N_i, ice particle formation rate $\frac{dN_i}{dt}$, and RH_w as functions of $z - z_b$.

The triggering RH_w range was reduced significantly, to less than 2% in Wh020L and 5% in Ch020L in comparison to 3% and 8% in Wh020 and Ch020. The predicted N_i is only marginally affected.

At the beginning of the nucleation stage in Wh020L, ice particle formation rates by the four T_{eff} models are close. However, models C and D reach much larger RH_w that leads to larger instantaneous nucleation rates, and maintain the peak ice formation rate longer than the other two models.

Quite contrarily, the N_i curves of models D and L in Ch020L distinctly separate from those of models C and S. This grouping incidentally coincides with the grouping according to the haze size specifications. Large haze particles are more concentrated than the corresponding equilibrium values in models C and S. Yet, the nucleation regime in model S was not sustained as long as in model C; a similar finding is noted when comparing results of model D and L. The results of model J feature slow ice particle formation rate, long nucleation duration, and broader freezing haze number distribution.

The above results indicate that nucleation duration time and the maximum nucleation rate achieved are the two key components in determining the final N_i. These two factors are sensitive to the growth rates of small ice crystals, which under the influence of the kinetic effect are sensitive to the deposition coefficient, β_i. It was found that varying β_i from 0.04 to 1 (Table 2) would result in about a factor of 4$\sim$5 (Wh020L) and 9$\sim$12 (Ch020L) variation in N_i by models C and L.

4 SUMMARY

Results of Phase 1 of CPMC projects show that the predicted cloud properties strongly depend on updraft speed. Significant differences are found in the predicted N_i. Detailed examination revealed that the homogeneous nucleation formulation, aerosol size specification, ice crystal growth (especially the specification of the deposition coefficient for ice) and water vapor uptake rate were the critical components. These results highlight the need for new laboratory and field measurements to infer the correct values for critical quantities in the cirrus regime.

No attempt was made to scrutinize the causes of differences in ALL-MODE simulations due to the substantial differences in formulation of heterogeneous nucleation. Nevertheless, it was confirmed that the expected effect of a heterogeneous nucleation process is to decrease N_i and the RH_i required for cloud initiation. Clearly, new measurements of ice nuclei activation in cirrus conditions are warranted.

CPMC Phase 1 was conducted based on a single CCN distribution. Phase 2 of the CPMC, now underway, examines the effects of varying aerosol distributions. Sensitivity of model results to CCN composition is indirectly made by altering λ.

5 ACKNOWLEDGMENT

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